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The high-temperature static failure mechanisms of several representative superalloys (Inconel 718, 800 and 783) were studied under controlled loading and environmental conditions. As part of this experimental program, high temperature Digital Image Correlation was applied to measure local deformation fields of fracture mechanics specimens. The measured deformations were compared to those predicted by various creep fracture theories and by finite element models. Such comparisons, combined with metallographic and fractographic evidence, support the theory that the micromechanisms of failure are strongly influenced by the occurrence of stress-accelerated grain boundary oxygen embrittlement. Consequently, a constitutive model that describes the combined effects of creep damage and oxygen embrittlement for superalloys at elevated temperatures and under oxidizing environments has been developed.

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CREEP, DAMAGE AND LIFE PREDICTION FOR HIGH TEMPERATURE MATERIALS

Final Report for Grant No. F49620-94-1-0448

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1. EXECUTIVE SUMMARY

This project was a combined experimental-theoretical investigation of creep, damage and crack growth behavior of metallic materials used in military and commercial gas turbine engines. Specific objectives of this research were to study the behavior of metallic materials at high temperature and in aggressive environments, to establish constitutive laws for creep and damage evolution in such materials, and to develop crack-growth models for life prediction of structural components.

The high-temperature static failure mechanisms of several representative superalloys (Inconel 718, 800 and 783) were studied under controlled loading and environmental conditions. As part of this experimental program, high temperature Digital Image Correlation was applied to measure local deformation fields of fracture mechanics specimens. The measured deformations were compared to those predicted by various creep fracture theories and by finite element models. Such comparisons, combined with metallographic and fractographic evidence, support the theory that the micromechanisms of failure are strongly influenced by the occurrence of stress-accelerated grain boundary oxygen embrittlement. Consequently, a constitutive model that describes the combined effects of creep damage and oxygen embrittlement for superalloys at elevated temperatures and under oxidizing environments has been developed.

This report is a summary of seven inter-related tasks that constitute this project. When the detailed descriptions of the experimental equipment, set up, procedures, computational methods and results are available in published form, the most significant papers and theses are cited. Otherwise, this summary includes those details.

1.1 High-Temperature Deformation Measurements Using Digital Image Correlation

The optical technique of Digital Image Correlation (DIC) was developed at the University of South Carolina. DIC can provide an accurate measurement of surface deformations, either at a point or over a field containing strain gradients. In the DIC method, a video camera and personal computer acquire digitized images of a random speckle pattern on the surface of a specimen before and after deformation. Displacements are calculated directly by correlating the two digital images. To correlate the deformed image to the undeformed reference image, each image is divided into small subsets. The discrete matrix of the pixel gray level values in each subset form a unique "fingerprint" identification within the image. A computer program correlates the subset pixel gray level matrices in the deformed and undeformed images and gives the horizontal and vertical displacements of the center point of each subset. As part of this research, the ability of the DIC method to measure full-field in-plane surface deformations at elevated temperatures was evaluated.

The experimental details and complete results are described in the paper "High-Temperature Deformation Measurements Using Digital-image Correlation", J.S. Lyons, J. Liu and M.A. Sutton, Experimental Mechanics, Vol. 36, No. 1, pp. 64-70 (1996).

Significant Findings. Two key precautions must be taken when applying the DIC method at elevated temperatures: heated air near the furnace window must be mixed to maintain a constant index of refraction, and all glass in the optical path must be of a high quality to prevent image distortion. Results of thermal expansion and uniform tension tests indicate that the DIC method is capable of measuring thermally and mechanically induced strains at temperatures up to 650°C with the same level of accuracy that is obtainable under ambient conditions.

1.2. Experimental Characterization of Crack Tip Deformation Fields in Alloy 718 at High Temperatures

A series of fracture mechanics tests were conducted at temperatures of 650 °C and 704 °C in air, using Inconel® 718. The non-contacting Digital Image Correlation technique was applied to directly measure surface displacement, strains, and displacement rates prior to and during creep crack growth. For the first time, *quantitative* comparisons at elevated temperatures are presented between experimentally measured near-crack-tip deformations fields and theoretical linear elastic and viscoelastic fracture mechanics solutions.

The experimental details and complete results are described in the paper "Experimental Characterization of Crack Tip Deformation Fields in Alloy 718 at High Temperatures," J. Liu, J.S. Lyons, M.A. Sutton and A.P. Reynolds, *Journal of Engineering Materials and Technology*, to appear in Vol. 120, (1998). This research also comprises a major part of the thesis "Computer Vision Measurement of Local Deformations During Creep Crack Growth of Superalloys," Jin Liu, Dissertation for Doctor of Philosophy in Mechanical Engineering, *University of South Carolina*, Columbia SC, 1997.

Significant Findings. The results establish that linear elastic conditions dominate the near-crack-tip displacements and strains at 650 °C, even during crack growth. Further, it is shown that the stress intensity factor, K_I, is a viable continuum-based fracture parameter for creep crack growth characterization. Post-mortem fractographic analyses indicate that grain boundary embrittlement leads to crack extension before a significant amount of creep occur at this temperature. At higher temperatures, however, no crack growth was observed due to a significant amount of crack tip blunting after load application. The time-dependence of the blunting process is interpreted as a transition from primary to steady-state creep deformation in the near-crack-tip region.

1.3. Finite Element Analysis of Creep Fracture in a Alloy 800

Detailed finite element analyses were performed for a single edge-cracked specimen geometry, under both plane stress and plane strain constraints as well as full three-dimensional conditions, for a superalloy material that obeys a power-law creep relationship. The objectives of these analyses were to elucidate the stationary creep crack-tip fields and to provide guidance for the experimental measurement of crack tip deformations.

Results from plane stress and plane strain studies were presented in "Crack-tip fields and singularity-dominance zone in a power-law creep superalloy," L. Yang, X. Deng and M. A. Sutton, at the 1996 ASME Applied Mechanics and Materials Summer Meeting, June 12-14, 1996, the Johns Hopkins University, Baltimore, Maryland. The computational details and more complete results for these two-dimensional cases are described in the paper "Finite Element Analysis of Creep Fracture in a Model Superalloy Material", L. Yang, M.A. Sutton, X. Deng and J.S. Lyons, International Journal of Fracture Mechanics, Vol. 81, No. 4, pp. 299-329 (1996). This research is also the basis of the thesis "Finite Element Analysis of Creep Fracture Initiation in a Model Superalloy Material", Lei Yang, Thesis for Master of Science in Mechanical Engineering, University of South Carolina, Columbia SC, 1996. Three-dimensional findings and comparisons with two-dimensional counterparts were discussed in "Finite Element Studies of Creep Fracture of a Power-Law Creep Superalloy," X. Deng, M. A. Sutton, L. Yang, and L. Sun, at the 33rd Annual Technical Meeting of the Society of Engineering Science, Oct. 20-23, 1996, Arizona State University, Tempe, Arizona.

Significant Findings. New results demonstrate that, for both plane stress and plane strain, the angular variations in the creep strain fields do not agree with HRR-type predictions, although the radial variations are in agreement with HRR-type creep strain field predictions in a zone very near the crack tip. Thus, the use of experimental measurement of surface displacement and/or strain data for the location of HRR-type fields may not be possible, unless modifications to the existing HRR-type theory are made. It is also noted that the size of the stress-based HRR dominance zone is quite small for both plane stress and plane strain; along $\theta = 0^{\circ}$, the dominance zone size is 950 μm for plane stress and 0.250 μm for plane strain. Furthermore, the dominance zones of the singular strain fields are at least two orders of magnitude smaller than the corresponding stress dominance zones. Furthermore, three-dimensional effects at the crack tip make the HRR-type singularity dominance zones even smaller. As such, unless the microstructural features of the material are smaller than the dimensions of the dominance zones, the basis for using stress or strain-based fracture parameters derived from the HRR-type fields for prediction of creep fracture initiation is unclear.

1.4. Experimental Investigation of near Crack Tip Creep Deformation in Alloy 800 at 650°C

The non-contacting experimental method of Digital Image Correlation was used to measure full field, time-dependent surface deformations in the crack-tip region for a stationary crack in Inconel 800 at 650°C. The near crack tip results are analyzed in terms of full-field contours, radial and angular variations, and the line-integral creep fracture parameters C(t) and C*. Quantitative comparisons are made between the near-tip measurements and predictions from far field measurements and finite element modeling.

The experimental details and complete results comprises a major part of the thesis "Computer Vision Measurement of Local Deformations During Creep Crack Growth of Superalloys," Jin Liu, Dissertation for Doctor of Philosophy in Mechanical Engineering, *University of South Carolina*, Columbia SC, 1997. This research is also under review for publication as "Experimental Investigation of Near Crack Tip Creep Deformation in Alloy 800 at 650°C," J. Liu, M. Sutton, J. Lyons and X. Deng, In review for *International Journal of Fracture* (submitted July 1997).

Significant Findings. For the first time, experimental results are obtained from measured near-crack-tip deformations that show that the C(t)-integral is initially time- and path-dependent but approaches a constant value C* over time. The near-tip strain data portrays trends similar to finite element method predictions that use an elastic power-law hardening material model. However, they are significantly different in magnitude. Also, the transition time obtained is about 10 times longer than that predicted by classical HRR solution. It is suggested that that primary creep should not be neglected for this material.

1.5. Effect of Aluminide Particle Distribution on the High Temperature Crack Growth Characteristics of a Co-Ni-Fe Superalloy

Inconel 783® is an oxidation-resistant, controlled coefficient of thermal expansion, cobalt-nickel-iron-based superalloy (1) with a Co-Ni-Fe based composition. It is a unique Co-based ally in that the matrix (γ) is FCC and is strengthened by coherent strengthening precipitates (γ'). It has been shown that an aluminum content greater than 5wt% leads to the formation of body-centered aluminide (β) particles and improved resistance to stress accelerated grain boundary oxygen (SAGBO) embrittlement relative to other low-expansion superalloys. In this research, a study was undertaken to determine the role of the β phase during creep crack growth, and how its

distribution affects the alloy's SAGBO resistance. The experimental program included static fracture testing at 583°C using four heat treatment conditions, fractography and quantitative compositional analysis on oxidized specimens.

The experimental details and complete results are described in the paper "Effect of Aluminide Particle Distribution on the High-Temperature Crack Growth Characteristics of a Co-Ni-Fe Superalloy," J.S. Lyons, A.P. Reynolds and J.D. Clawson, *Scripta Materialia*, Vol. 37, No. 7, pp. 1059-1064 (1997). This research also comprises a major part of the thesis "Microstructural Influences on the Creep Crack Growth Behavior of Superalloy Inconel 783," James D. Clawson, Jr., Thesis for Master of Science in Mechanical Engineering, *University of South Carolina*, Columbia, SC, 1996.

Significant Findings. Results show that aging of alloy 783 to produce a continuous grain boundary film of β phase results in reduced creep crack growth rates at 538°C compared to heat treatments which do not result in a continuous film. Oxidation studies indicate that the β phase is oxidation resistant and hence may cause increased resistance to SAGBO.

1.6. A Constitutive Model for Creep and Stress-Accelerated Grain Boundary Oxygen Embrittlement of Superalloys

The objective of this research is to develop and experimentally verify a constitutive model that describes the combined effects of creep and stress-accelerated grain boundary oxygen embrittlement (SAGBO) for superalloys at elevated temperatures and under oxidizing environments. Building on the successful completion of recent superalloy research for Inconel 718 and 783 (which exhibit SAGBO effects at elevated temperature) and Incoloy 800, we are developing the ***first constitutive model*** for characterizing the coupled oxidation kinetics, oxygen diffusion and damage evolution processes which occur in such materials. The model will incorporate ***two unique physical time scales***, one for oxidation processes and one for diffusion in the material. It is important to note that *all parameters in the model can be determined systematically from three sets of tests performed on specimens with simple geometrical shapes* (e.g., bars); (a) oxidation tests, (b) creep tests in a vacuum and (c) creep tests in an oxidizing environment. This research will be used to develop predictive capability for high temperature applications, including crack growth in critical components, when materials embrittled by long-term exposure to an oxidizing environment are used.

This recently initiated research task will be published as "Modeling oxygen embrittlement of superalloys at elevated temperatures," F. Ma, X. Deng and M. A. Sutton, 13th U.S. National Congress of Applied Mechanics, June 21-26, 1998, the University of Florida, Gainesville, Florida. Since the results have not yet appeared in an archival publication, a detailed description of the constitutive model development is included here.

DESCRIPTION OF THE CONSTITUTIVE MODEL

1. MOTIVATION AND OBJECTIVE

A number of creep-resistant superalloys (e.g. Incoloy 718) developed for turbine engine applications suffer from stress-accelerated grain-boundary oxygen embrittlement (SAGBO). The exact mechanism in which oxygen embrittles the grain boundary is still a matter of debate, and a phenomenological theory that describes the SAGBO effect does not exist. As such, a framework for modeling and predicting elevated-temperature behavior, especially crack growth behavior, for superalloys with SAGBO is lacking.

Our broad objective is to develop a ***phenomenological theory*** to characterize the combined effect of creep and SAGBO in the form of *a constitutive model.* This model will incorporate four coupled processes of the SAGBO phenomenon: (a) void nucleation, growth and coalescence through conventional creep mechanisms, (b) stress-accelerated oxygen diffusion into the bulk of a material along grain boundaries; (c) formation of brittle oxides along the grain boundaries and breakage of the oxides under tensile stresses; (d) initiation and accumulation of damage due to loss of load-carrying material volume as a result of the presence of voids and oxides.

Four types of tests will be conducted: oxidation tests, creep tests in a vacuum and creep tests in oxidizing environments will be used to obtain model parameter values and to verify the model's bulk behavior prediction; and finally creep crack growth tests will be used to validate the model's creep fracture behavior prediction.

2. CONSTITUTIVE MODEL DEVELOPMENT

2.1 OVERVIEW

The proposed constitutive model introduces a scalar *damage variable*, ω, as a material internal variable. It is defined as the ratio of the damaged (non-load carrying) material volume, V_d, to the total material volume, V, of a representative material element. *Damage is attributed to two sources*, one due to conventional creep damage, through void nucleation, growth and coalescence, and one due to oxidation embrittlement, through oxide formation and breakage. To predict the damage evolution process, the constitutive model incorporates (a) an *oxidation law* to describe the rate of oxide formation, (b) a *diffusion equation* to model the diffusion of oxygen along grain boundaries, (c) a *potential function* to relate strain rate to stress and damage, and (d) a *damage evolution relationship* to characterize the growth of damage.

Three sets of parameters are introduced in the model. **The first set** characterizes the oxidation process and can be determined from *a standard oxidation curve* from oxidation tests. **The second set** characterizes the creep behavior in vacuum, and can be determined from *a standard creep curve* from conventional creep tests in vacuum. The initial portion of the creep curve represents the creep behavior (a power-law) before noticeable damage occurs and can be used to determine B and n (see Eq. (4)). The latter portion of the curve then can be used to determine damage parameters c_1 (damage induced stress concentration coefficient) and c_2 and c_3 (stress triaxiality coefficients) (see Eq. (5)). **The third set** characterizes the effect of oxygen embrittlement and can be determined from *a standard creep curve* from conventional creep tests in an oxidizing environment (e.g. air). This creep curve can be used to determine A_0 and m for the effect of stress on oxygen embrittlement (see Eq. (7)). Specimens from interrupted creep tests can be cut and the cross sections can be chemically analyzed for oxygen concentration distribution, so that the *diffusivity* D for the oxygen diffusion process can be determined (see Eq. (1)).

2.2 DIFFUSION EQUATION

At the continuum scale, the diffusion of oxygen along grain boundaries can be viewed as a volume diffusion process and is governed by (Crank, 1975)

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}\right) \tag{1}$$

where variable C is the *oxygen concentration* at a point and is a function of position and time, and D is the *diffusivity* parameter and may depend on *temperature* T and stress state. *The diffusion process introduces an important time scale into the constitutive model.*

2.3 OXIDATION LAW

When a material is uniformly oxidized in an environment with a constant oxygen concentration, oxide production can be described by an empirical oxidation law, which relates the amount of oxide produced, $P(t)$, to oxygen concentration C and exposure time t. For example, the Logarithmic Reaction Law (Fontana and Grene, 1969) is given by

$$P(t) = k\log(\alpha t+\beta) \tag{2}$$

where k, α and β are *oxidation parameters* that may depend on C. The *rate of oxidation*, $R_0(t)$, is then determined by differentiating $P(t)$ with respect to time while holding the oxidation parameters constant. If these parameters depend on C and C varies with time (e.g. due to oxygen diffusion), then the rate of oxidation must be determined based on the Boltzmann superposition principle. For example, suppose in Eq. (2) α and β are constant and k depends on C, then the rate of oxidation can be shown to be

$$R(t) = R_o(t)H(t) + \int_0^t \frac{\partial R_0}{\partial k}\frac{\partial k}{\partial C}\frac{\partial C}{\partial \tau}H(t-\tau)d\tau \tag{3}$$

where $H(t)$ is the Heaviside function. *The oxidation law introduces another important time scale into the constitutive model.*

2.4 STRAIN-RATE POTENTIAL FUNCTION

We introduce the following potential function Ψ for the creep strain rate $\dot{\varepsilon}_{ij}$:

$$\Psi = \frac{B\Phi^{n+1}}{n+1} \text{ so that } \dot{\varepsilon}_{ij} = \frac{\partial\Psi}{\partial\sigma_{ij}} \tag{4}$$

where B and n are creep parameters, and

$$\Phi = \frac{\sigma_e g(\omega,\chi)}{(1-c_1\omega)^{n/n+1}},\ g(\omega,\chi) = \sqrt{1+c_1\omega\exp(c_2\chi+c_3)},\ \chi = \left\langle\frac{3\sigma_m}{2\sigma_e}\right\rangle \tag{5}$$

In the above, σ_m is the mean stress, σ_e is the von Mises effective stress, parameter c_1 is the coefficient for the damage variable ω and accounts for the stress concentration effect of damage, and parameters c_2 and c_3 describe the effect of stress triaxiality denoted by χ. Note that χ equals the value of the content in the angle bracket $\langle\ \rangle$ if the content is positive and it is zero if the content is negative. Note that while Eq. (4) resembles that used, e.g. by Cocks (1989), Equation (5) differs from those by previous investigators. We note that the forms for Φ in existing potential functions do not account for the effect of stress concentration due to damage, and consequently greatly underestimate the creep rate and do not compare well with test data in the literature (e.g. see Fig. 1).

2.5 DAMAGE EVOLUTION

We propose that the *rate of damage growth* consists of two components, one due to creep deformation through void nucleation, growth and coalescence, and one due to oxidation embrittlement, through oxide formation and breakage. That is

$$\dot{\omega} = \dot{\omega}_{creep} + \dot{\omega}_{oxygen} \tag{7}$$

where the components are given by

$$\dot{\omega}_{creep} = (1-\omega)\dot{\varepsilon}_{kk}\,, \quad \dot{\omega}_{oxygen} = A_0 \langle \sigma_p \rangle^m R(t) \tag{8}$$

where A_0 and m are *oxidation embrittlement parameters* and σ_p is the maximum principal stress. The functional form for $\dot{\omega}_{creep}$ is based on that in vacuum (which can be derived from the definition of ω and the assumption that volume strain is mostly contributed by damage), and the functional form for $\dot{\omega}_{oxygen}$ is based on observations of the SAGBO phenomenon in which damage due to embrittlement is accelerated by tensile stresses and on the assumption that embrittlement does not occur at a zero tensile stress. More general forms for $\dot{\omega}_{oxygen}$ can be proposed, for example, by introducing a *threshold* tensile stress below which embrittlement will not occur. *The parameters A_0 and m can be determined from standard creep tests in an oxidizing environment in the form of a creep curve.*

2.6 PRELIMINARY RESULTS

Five creep curves from round-bar specimens made of a 0.5CrMoV steel are available from the literature (no creep curves are available for superalloys). Two curves are obtained at T=640^{0}C and σ=43MPa (one curve for vacuum and the other for air) and three curves at T=675^{0}C and σ=70PMa, for specimens of different diameters, all done in air. As shown in Figs. 1 and 2, with *crude approximations* for the oxidation and diffusion parameters due to lack of actual data, and *using averaged damage over the radius of the specimen*, the constitutive model can *fit one creep curve in air* to obtain the parameters and use these parameter values to *predict other creep curves both in air and in vacuum.* Figure 1 shows the comparisons with creep tests conducted at T=640^{0}C and σ=43MPa and Figure 2 shows the comparisons with creep tests performed at T=675^{0}C and σ=70MPa. In both figures, the symbols denote test data, and the lines are the predictions based on the constitutive model. While the current model compares well with test data both in vacuum and in air, the prediction by previous theories (e.g. Cocks, 1989) is valid only in vacuum and greatly underestimates the creep strain rate at long times (see Fig. 1).

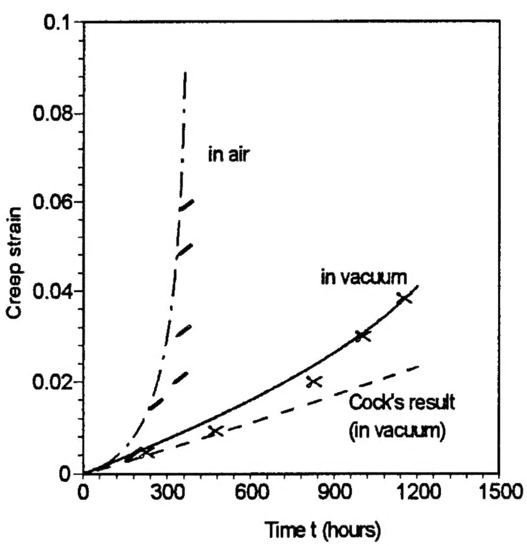

Fig. 1 Tested in air and vacuum at 640^{0}C and 43MPa

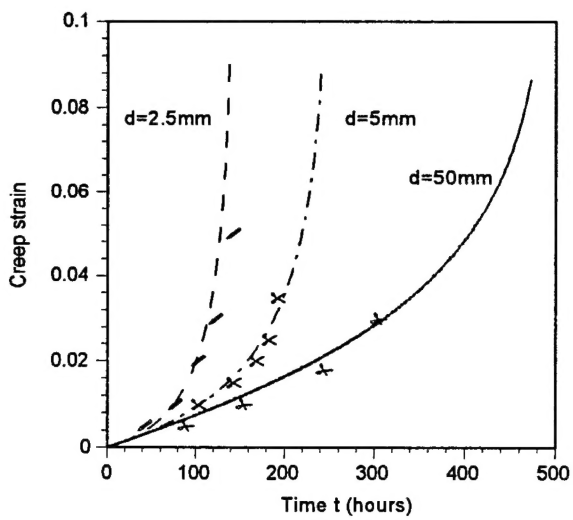

Fig.2 Tested at 675^{0}C and 70Mpa in air

REFERENCES FOR SECTION 1.6
Cocks, A.C.F. 1989. Inelastic deformation of porous materials. *J. Mech. Phys. Solids* 37, 693-715.
Crank, J. 1975. *The mathematics of diffusion.* Clarendon Press, Oxford.
Fontana, M.G. and Greene, N.D. 1967. *Corrosion Engineering.* McGraw-Hill. Inc.
Osgerby, S. and Dyson, B.F.. 1990. Effects of oxygen on creep performance: mechanisms and predictive modeling. *Materials Science and Technology* 6, 2-8.

1.7. Constraint Effects In Fracture Initiation

Variations of apparent fracture toughness under predominantly brittle fracture were investigated. Williams' asymptotic series solutions including higher order terms were used to characterize the crack tip stress and strain fields for various specimen geometries. It was demonstrated that material's resistance to fracture can be quantified by two mechanics parameters, K and A_3, for stress-controlled fracture; or K and T for strain-controlled fracture. Test data, which covers a wide range of T and A_3, was used to demonstrate the proposed fracture assessment procedure. Constraint related issues such as size, crack depth, and biaxial stress effect were investigated (see attached paper for details). The failure locus was discussed relative to the ASTM recommended specimen geometries.

The procedures and complete results are described in the papers: "Constraint Effect in Brittle Fracture," Chao, Y.J. and Zhang, X. H., *Fatigue and Fracture Mechanics: 27th Symposium*, ASTM STP 1296, R.S. Piascik, J.C. Newman, and D.E. Dowling, Eds., ASTM, 1997, pp. 41-60; "Fracture of Surface Cracks under Bending Loads," Chao, Y.J. and Reuter, W. G., ASTM STP 1321, *Fatigue and Fracture Mechanics: 28th Volume,* J.H. Underwood, B. MacDonald, and M. Mitchell, Eds., 1997, pp. 214-242; "Effects of Crack Depth, Specimen Size, and out-of-plane Stress on the Fracture Toughness of Reactor Vessel Steels," Chao, Y.J. and Lam, P.S., ASME Journal of Pressure Vessel Technology, vol. 118, No. 4, pp.415-423 (1996); and "Effects of Crack Depth, Specimen Size, and Out-of-Plane Stress on the Fracture Toughness of Reactor Vessel Steels: An Analytical Study," Y.J. Chao and P.S. Lam, *Fatigue and Fracture Mechanics in Pressure Vessels and Piping*, H.S. Mehta, editor, ASME publication, PVP-Vol.304, pp.81-90, 1995.

The analysis is then extended to metallic materials under creep conditions. The asymptotic series solution for materials under elastic power-law creep conditions is derived first. Application and interpretation of the mathematical solution to creeping solids are then demonstrated by comparing the mathematical solutions with finite element results. It is shown that while the amplitude of the singular term C* determines the loading the second parameter A_2 can be used to describe the specimen geometry; thus the "constraint effect". More specifically, with both C* and A_2 the zone at the crack tip dominated by the asymptotic solution is large and exists for essentially all test specimen geometries and structural members. The result from this work is in the MS thesis by Zhang Li, entitled "Characterization of crack tip fields under steady-state creep using HRR and higher order terms". The results will be published later.

Significant Findings. It was shown that the ASTM in-plane size requirements place a finite size window on the complete material failure locus. Due to variations in in-plane geometry, real

structures may possess constraint levels either higher or lower than the ASTM standard test specimens, and may fracture at an applied K either higher or lower than K_{IC}. It was also demonstrated that K_{IC} determined according to ASTM E399 and based on a linear elastic solution is not conservative to predict the fracture of specimens with low in-plane constraint geometries. This trend was opposite to the corresponding constraint effect when the crack tip deformation at fracture is characterized by large scale yielding. When applied to materials with creep behavior, the trend is similar through our comparison to the results from finite element analysis.

1.8. Conclusion

The high-temperature static failure mechanisms of several representative superalloys (Inconel 718, 800 and 783) were studied under controlled loading and environmental conditions. As part of this experimental program, high temperature Digital Image Correlation was applied to measure local deformation fields of fracture mechanics specimens. The measured deformations were compared to those predicted by various creep fracture theories and by finite element models. Such comparisons, combined with metallographic and fractographic evidence, support the theory that the micromechanisms of failure are strongly influenced by the occurrence of stress-accelerated grain boundary oxygen embrittlement. Consequently, a constitutive model that describes the combined effects of creep damage and oxygen embrittlement for superalloys at elevated temperatures and under oxidizing environments has been developed.

2. PERSONNEL SUPPORTED

The following faculty and students received support from this grant during the reporting period.

Faculty:	Dr. Michael A. Sutton, Professor Dr. Bill Y.J. Chao, Professor Dr. Xiaomin Deng, Associate Professor Dr. Jed S. Lyons, Assistant Professor
Post Docs:	Dr. Wei Zhao Dr. Fashang Ma
Students:	Lei Yang, Master of Science James Clawson, Master of Science Ming Xin Zhao, Master of Science Hua Jiang, Master of Science Jin Liu, Doctor of Philosphy Liankui Sun, Doctor of Philosophy Li Zhang, Master of Science

3. DISSEMINATION OF RESULTS

The following publications and presentations acknowledged the support of this grant.

Theses

"Computer Vision Measurement of Local Deformations During Creep Crack Growth of Superalloys," Jin Liu, Dissertation for Doctor of Philosophy in Mechanical Engineering, *University of South Carolina,* Columbia SC, 1997.

"Finite Element Analysis of Creep Fracture Initiation in a Model Superalloy Material", Lei Yang, Thesis for Master of Science in Mechanical Engineering, *University of South Carolina,* Columbia SC, 1996.

"Microstructural Influences on the Creep Crack Growth Behavior of Superalloy Inconel 783," James D. Clawson, Jr., Thesis for Master of Science in Mechanical Engineering, *University of South Carolina,* Columbia, SC, 1996.

"Effect of Heat Treatment and Environment on the High Temperature Fatigue of a Controlled Expansion Superalloy," H. Jiang, Thesis for Master of Science in Mechanical Engineering, *University of South Carolina,* Columbia, SC, (expected 1998).

"Characterization of Crack Tip Fields under Steady-State Creep Using HRR and Higher Order Terms," Li Zhang, Thesis FOR Master of Science in Mechanical Engineering, *University of South Carolina,* Columbia , SC , 1997.

Publications

"Experimental Characterization of Crack Tip Deformation Fields in Alloy 718 at High Temperatures," J. Liu, J.S. Lyons, M.A. Sutton and A.P. Reynolds, *Journal of Engineering Materials and Technology*, to appear in Vol 120, (1998).

"Effect of Aluminide Particle Distribution on the High-Temperature Crack Growth Characteristics of a Co-Ni-Fe Superalloy," J.S. Lyons, A.P. Reynolds and J.D. Clawson, *Scripta Materialia*, Vol. 37, No. 7, pp. 1059-1064 (1997).

"Constraint Effect in Brittle Fracture," Chao, Y.J. and Zhang, X. H., *Fatigue and Fracture Mechanics: 27th Symposium*, ASTM STP 1296, R.S. Piascik, J.C. Newman, and D.E. Dowling, Eds., ASTM, pp. 41-60 (1997).

"Experimental Investigation of Near Crack Tip Creep Deformation in Alloy 800 at 650°C," J. Liu, M. Sutton, J. Lyons and X. Deng, In review for *International Journal of Fracture* (submitted July 1997).

"Fracture of Surface Cracks under Bending Loads," Chao, Y.J. and Reuter, W. G., ASTM STP 1321, *Fatigue and Fracture Mechanics: 28th Volume,* J.H. Underwood, B. MacDonald, and M. Mitchell, Eds., 1997, pp. 214-242.

"Measuring Microscopic Deformations with Digital Image Analysis Method," Z. Sun, J.S. Lyons and S.R. McNeill, *Optics and Lasers in Engineering,* Vol. 27, pp. 409-428 (1997).

"Improved Three-Dimensional Image Correlation for Surface Displacement Measurement J.D. Helm, S.R. McNeil and M.A. Sutton," *Optical Engineering,* 35(7) pg. 1911-1920, (1996).

"Finite Element Analysis of Creep Fracture in a Model Superalloy Material", L. Yang, M.A. Sutton, X. Deng and J.S. Lyons, *International Journal of Fracture Mechanics,* Vol. 81, No. 4, pp. 299-329 (1996)

"Effects of Crack Depth, Specimen Size, and out-of-plane Stress on the Fracture Toughness of Reactor Vessel Steels," Chao, Y.J. and Lam, P.S., ASME Journal of Pressure Vessel Technology, vol. 118, No. 4, pp.415-423 (1996)

"High-Temperature Deformation Measurements Using Digital-image Correlation", J.S. Lyons, J. Liu and M.A. Sutton, Experimental Mechanics, Vol. 36, No. 1, pp. 64-70 (1996).

"Effects of Crack Depth, Specimen Size, and Out-of-Plane Stress on the Fracture Toughness of Reactor Vessel Steels: An Analytical Study," Y.J. Chao and P.S. Lam, *Fatigue and Fracture Mechanics in Pressure Vessels and Piping*, H.S. Mehta, editor, ASME publication, PVP-Vol.304, pp.81-90, 1995.

"Effects of Crack Depth, Specimen Size, and Out-of-Plane Stress on the Fracture Toughness of Reactor Vessel Steels: An Analytical Study," Y.J. Chao and P.S. Lam, *Fatigue and Fracture Mechanics in Pressure Vessels and Piping*, H.S. Mehta, editor, ASME publication, PVP-Vol.304, pp.81-90, 1995.

Presentations

"Modeling oxygen embrittlement of superalloys at elevated temperatures," F. Ma, X. Deng and M. A. Sutton, submitted for presentation at the 13th U.S. National Congress of Applied Mechanics, June 21-26, 1998, the University of Florida, Gainesville, Florida.

"Near Crack Tip Creep Deformation Measurements in Alloy 800 at 650°C," Presentation by J.S. Lyons at the Joint *ASM-TMS Materials Week '97*, Indianapolis, Indiana, 15 September 1997.

"Microstructural Influences on the Deformation and Fracture of a Low-Expansion Superalloy," Presentation by J.S. Lyons at *ASM-TMS Materials Week '96*, Cincinnati, Ohio, 7 October 1996.

"Finite Element Studies of Creep Fracture of a Power-Law Creep Superalloy," X. Deng, M.A. Sutton, L. Yang, and L. Sun, presentation at the 33rd Annual Technical Meeting of the Society of Engineering Science, Oct. 20-23, 1996, Arizona State University, Tempe, Arizona.

"Crack-tip fields and singularity-dominance zone in a power-law creep superalloy," L. Yang, X. Deng and M.A. Sutton, presentation at the 1996 ASME Applied Mechanics and Materials Summer Meeting, June 12-14, 1996, the Johns Hopkins University, Baltimore, Maryland.

"Deformation and Fracture Measurements and Mechanisms in Alloy 718 at High Temperature," Invited presentation by J.S. Lyons at the *ASME-MD Summer Meeting*, Los Angeles CA, 28 June 1995.

"Constraint Effect in Brittle Fracture," Y.J. Chao, presented at the *27th ASTM Fracture Symposium*, Williamsburg, VA, June 1995.

"Effects of Crack Depth, Specimen Size, and Out-of-Plane Stress on the Fracture Toughness of Reactor Vessel Steels : An Analytical Study," Y.J. Chao, presented at the 1995 Joint ASME/JSME Pressure Vessels and Piping Conference, Honolulu, Hawaii, July 25, 1995.

"Fracture of Surface Cracks under Bending Loads" Y.J. Chao, presented at the ASTM 28th National Symposium on *Fatigue and Fracture Mechanics*, Saratoga Spring, New York, June 25-27, 1996.